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## The $\beta$ -decay approach for studying $^{12}\text{C}$

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**Abstract.** The  $\beta$ -decays of the mirror nuclei  $^{12}\text{B}$  and  $^{12}\text{N}$  both populate states in  $^{12}\text{C}$  and they are therefore a precious source of information about this nucleus. Due to the selection rules of  $\beta$ -decay only  $0^+$ ,  $1^+$  and  $2^+$  states are populated. This allows a very clean study of unbound states just above the  $3\alpha$ -threshold with those spin and parities. This probe has been applied in two experiments using two complementary experimental techniques: in the first the three  $\alpha$ -particles emitted after  $\beta$ -decay are measured in coincidence in separate detectors using the ISOL method, while in the second method  $^{12}\text{B}$  and  $^{12}\text{N}$  are implanted in a detector and the summed energy of the three  $\alpha$ -particles is measured directly. Preliminary results from the two approaches are presented.

### 1. Introduction

The cluster structure of  $^{12}\text{C}$  has been discussed since the early days of nuclear physics, but experimentally there are today still important open questions on the existence of  $0^+$  and  $2^+$  states above the  $3\alpha$  threshold at 7.275 MeV [1] with consequences for nuclear structure and astrophysics [2, 3, 4]. In the latest  $^{12}\text{C}$  review from 1990 [1] there are no unambiguously identified  $0^+$  or  $2^+$  T=0 states above the  $0^+$  state at 7.654 MeV. Most nuclear structure models predict more  $0,2^+$  states in the first 1-10 MeV above the  $3\alpha$ -threshold, perhaps the most famous prediction is Morinaga's conjecture that the 7.654 MeV state has a structure of three  $\alpha$ -particles in a chain and therefore is very deformed [5]. The  $2^+$  rotation is predicted to be about 2 MeV

above the  $0^+$  state and it was therefore first suggested that a known state at 9.6 MeV state was this rotation, but this was later assigned as a  $3^-$  state [1]. When a broad state was later seen in  $\beta$ -decay [6] Morinaga suggested this was the missing  $2^+$  state [7]. In fact the  $\beta$ -decay work [8] was partly motivated by this suggestion. With more sophisticated calculations in the late 1970s the nature of the 7.654 MeV state was suggested to be more gas-like, but the prediction of a low lying  $2^+$  state remained [9]. More recently the gas-like nature of the 7.654 MeV state is discussed in the context of Bose condensation [10]. It is unclear if there is any real new insight gained by the notion of Bose condensates in nuclei.

There are several recent experimental suggestions for the existence of  $2^+$  states above the 7.654 MeV state. Two groups use inelastic  $\alpha$ -particle scattering on  $^{12}\text{C}$ , but arrive at different positions for the state, 11.4 MeV and 10 MeV respectively, which illustrates the difficulty [11, 12, 13]. It seems here that the latter work with an impressive resolution of the measured spectrum is most reliable. Very recently Freer *et al.* [14] have presented evidence for a state using the  $^{12}\text{C}(^{12}\text{C},3\alpha)$  reaction, which is in good agreement with [11], although the state is very weakly populated in this reaction.

Here we will discuss recent results obtained using the  $\beta$ -decays of  $^{12}\text{B}$  and  $^{12}\text{N}$  as a probe of  $^{12}\text{C}$  structure. We first summarize previous work using this probe in section 2, then present new results in section 3, and finally give an outlook.

## 2. Overview of previous results using $\beta$ -decay

The  $\beta$ -decays of the mirror nuclei  $^{12}\text{B}$  and  $^{12}\text{N}$  both populate states in  $^{12}\text{C}$  and they are therefore a precious source of information about this nucleus.  $\beta$ -decay as a probe has some advantages over reactions. Allowed decays of  $^{12}\text{B}$  and  $^{12}\text{N}$  can populate  $0^+$ ,  $1^+$  and  $2^+$  states in the daughter  $^{12}\text{C}$ , this helps to remove contributions from several other resonances with different spin-parity in the region of interest. Also, the strength of the population (log ft-value) is related to the amount of cluster component in the populated state in  $^{12}\text{C}$ , see e.g. [15].

There is a substantial literature on experimental studies of the  $^{12}\text{B}$  and  $^{12}\text{N}$  decays, however, the attention has in the past almost 40 years mainly focused on decays populating the ground state and the first excited 4.44 MeV state; prior to 2001 the latest published measurement of  $\alpha$ -particles from the unbound states was completed in 1966 [8].

To improve on this we chose to initiate a campaign combining the information from both  $^{12}\text{N}$  and  $^{12}\text{B}$  decays: The  $\beta\nu$  phase-space distorts the broad states differently when they are populated in the two decays due to the difference in  $Q_\beta$ , and therefore a combined analysis should be less sensitive to systematic errors. Our first data for  $^{12}\text{N}$  were collected in 2001 at the IGISOL facility of the Jyväskylä Accelerator Laboratory, Finland, using the  $^{12}\text{C}(\text{p,n})^{12}\text{N}$  reaction, while for  $^{12}\text{B}$  first data came from CERN-ISOLDE in 2002 using an indirect production path via  $^{12}\text{Be}$ . A preliminary report on the analysis of the combined data is given in the proceeding [16], final results including a new calculation of the rate of the triple- $\alpha$  reaction is given in [17], and a detailed description of the  $^{12}\text{B}$ -results is given in [18].

The results are briefly summarized in the following. When corrected for  $\beta\nu$  phase-space and detection efficiencies the two data sets are mutually consistent. The resulting distribution cannot be fitted with the assumption of a single  $0^+$  or  $2^+$  state, but when interference with the 7.654 MeV state is included the data can be well described. This interference only works if this broad state in  $^{12}\text{C}$  is a  $0^+$  state. In the  $^{12}\text{N}$  data, which extends to higher energies, there is clear evidence for a new state, which is assigned as a  $2^+$  state because a fit with three interfering  $0^+$  states is unable to describe the data.

## 3. New experiments

In 2004 (in Jyväskylä) and again in 2006 (at the KVI, The Netherlands) we have revisited these decays for the following reasons. Our first set of experiments had a poor coverage for

decays where the three  $\alpha$ -particles share the breakup energy more or less equally, and hence the extent that such channels contribute could not be accurately extracted. Also, we were unable to extract the branching ratios with which the observed states were populated from the first set of data. Preliminary results and more discussion on these experiments can also be found in [19, 20] (Jyväskylä data) and [21] (KVI data).

### 3.1. New data from IGISOL

During 2004 new measurements of the decays of both  $^{12}\text{B}$  and  $^{12}\text{N}$  were carried out, this time both at the IGISOL facility of the Jyväskylä Accelerator Laboratory, Finland. The detection setup used in both of the old measurements (2001-2002) consisted of two opposing DSSDs. This geometry is ideal for measuring decay channels involving the ground state of  $^8\text{Be}$  since there the kinematics is such that coincidences will be near 180 degrees. However, the data did in fact contain events with decays different from this simple picture for both the broad  $0^+$  state and also from the new  $2^+$  state. Therefore we designed a setup with better coverage for decay channels with more uniform direction of emission. An additional limitation with the old data is that they cannot be used to extract branching ratios and logft values because they lack absolute normalization. Therefore we also included a Ge-detector in the new measurements such that by counting the number of detected 4.44 MeV gamma-rays the number of decayed  $^{12}\text{B}$  and  $^{12}\text{N}$  nuclei can be determined.

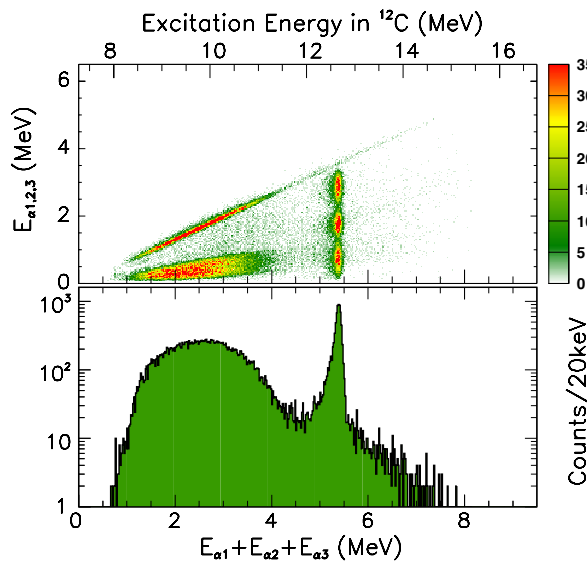
Fig. 1 and Fig. 2 give an overview of the data obtained in the new measurement for  $^{12}\text{N}$  and  $^{12}\text{B}$  respectively. The upper part shows a contour plot with the reconstructed excitation energy in  $^{12}\text{C}$  against each of the three individual energies, hence each break-up event is represented by three dots on the same vertical line; the lower part of the figure shows the projection onto the excitation energy axis. The narrow diagonal on the scatter plots is indicative of breakup of the  $^{12}\text{C}$  state into three  $\alpha$ -particles sequentially via the narrow  $^8\text{Be}$  ground state. Note that this diagonal extends up to more than 15 MeV in the  $^{12}\text{N}$  data giving unambiguous evidence for a state at higher energy, as also seen in the first round of experiments.

In the projections the 12.71 MeV state is readily identified in each decays; in the old data it was not observed because the acceptance for such breakups was much less. Note, this is the first time this state is observed in the  $^{12}\text{B}$  decay. The branching ratio is of the order of  $6 \times 10^{-6}$ . The break-up pattern of this state is clearly different from the events on the diagonal with the  $\alpha$ -energies here distributed in three separated regions.

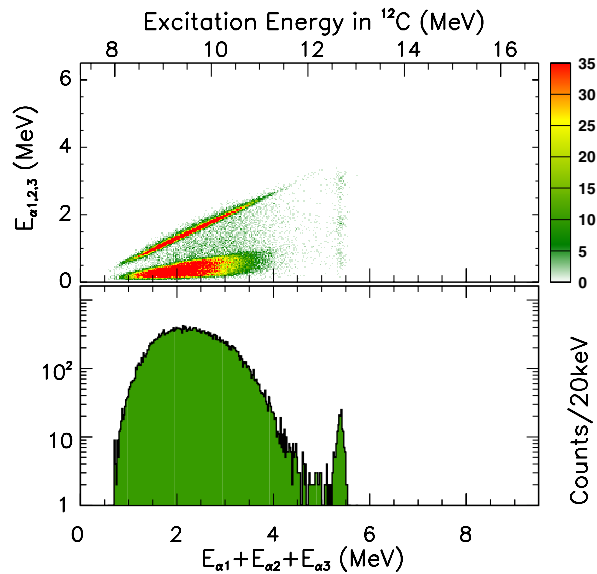
In both Fig. 1 and Fig. 2 events away from the diagonal can clearly be identified also for the broad states. These events cannot be background because they have passed a number of checks as detailed in [18]. There are of the order of 2000 such events in triple-coincidence in both of the two decays and the analysis and interpretation of them is ongoing. It can already be concluded that after correction for  $\beta\nu$  phase-space and efficiency the data-sets from the two decays are consistent with coming from the same distribution. These events are of particular interest because the angular correlation in the decay sequence  $^{12}\text{C}(J^\pi) \rightarrow ^8\text{Be}(2^+) + \alpha$  is different for  $0^+$  and  $2^+$  states, hence by studying this independent information on the spins may be extracted.

### 3.2. KVI data

Our approach of using ISOL beams stopped in a thin catcher and segmented Si-detectors has been demonstrated to be powerful, but it suffers from an inevitable low-energy cut-off from the fact that the  $\alpha$ -particles must first leave the collection foil and then pass through a detector dead-layer before they can enter the active area of the detector. Therefore, with the correlations between the  $\alpha$ -particles ( $\alpha$ - $\alpha$  coincidences) now well-measured we have in a sense completed our campaign with an approach that enable us to go beyond the low energy cut-off inherent in the ISOL approach. Such an approach was already demonstrated for  $^{12}\text{B}$  in [22] where this isotope



**Figure 1.** Complete kinematics data for the breakup of unbound states in  $^{12}\text{C}$  fed in the  $\beta$ -decay of  $^{12}\text{N}$ . The upper part shows reconstructed excitation energy in  $^{12}\text{C}$  against the individual  $\alpha$ -particle energies. The lower part shows the projection on the sum-energy axis.



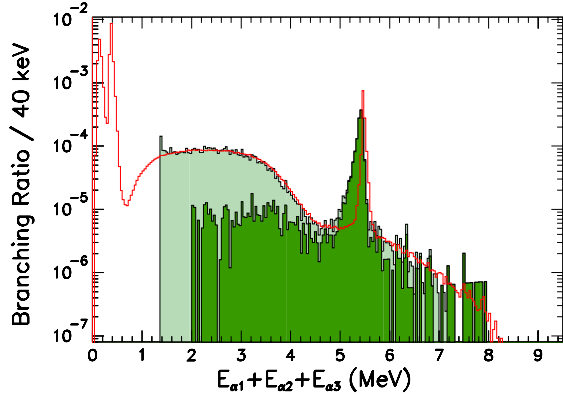
**Figure 2.** As Fig. 1, but data for the decay of  $^{12}\text{B}$ .

was implanted in a  $11\mu\text{m}$  thick Si surface barrier detector and the subsequent decay measured inside the detector. This thickness only permitted the 7.654 MeV state to be measured.

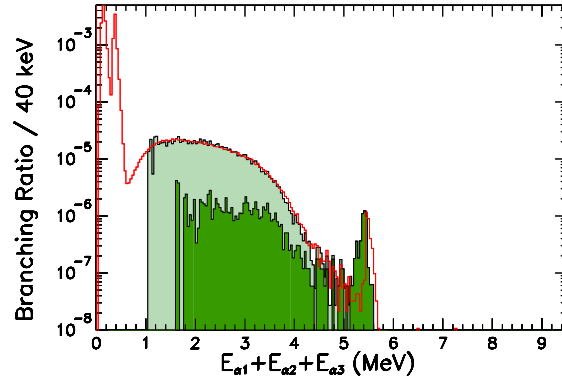
Another advantage with the new method is the possibility to measure absolute branching ratios to the states by comparing the number of implanted nuclei with the number of subsequent decays in the detector. This will provide branching ratios independent of the ones obtained from our IGISOL experiment.

Our implantation experiment took place at the KVI (Kernfysisch Versneller Instituut) in Groningen, the Netherlands in April 2006. At this facility it was possible for us to produce beams of  $^{12}\text{B}$  and  $^{12}\text{N}$ , and to get a very good separation of contaminants in the beams. We used a beam of  $^{12}\text{C}$  impinging on a hydrogen gas target to produce  $^{12}\text{N}$ , and a  $^{11}\text{B}$  beam on deuterium gas to produce  $^{12}\text{B}$ . The separator of the TRIUMF facility [24] then filtered the beam for contaminants and defocused the beam to take advantage of the entire detector area. The detector consists of  $48 \times 48$  strips with an active area of  $16 \times 16 \text{ mm}^2$  [25]. With a thickness of  $78\mu\text{m}$   $\alpha$ -particles from the decay of a nucleus implanted in the centre of the detector will deposit all of their energy inside the detector.

Decay spectra for  $^{12}\text{N}$  and  $^{12}\text{B}$  are shown in figure 3 and 4 respectively. The ordinate is branching ratio per bin which is calculated from the ratio between the number of implantations and the number of subsequent decays in each pixel of the detector. The data is compared to data from the IGISOL experiment (shown in Figure 1 and 2) which have been corrected for detection efficiency and also brought to an absolute scale by using the data from the Ge-detector in that experiment. For the IGISOL data both the total data as data with a gate on break-ups not going via the ground state in  $^8\text{Be}$  are shown.



**Figure 3.** In red data from  $^{12}\text{N}$  implanted in a segmented detector. In this case the total energy of the three emitted  $\alpha$ -particles is deposited in the detector together with a small energy from the  $\beta$ -particles. The data is compared to data from the IGISOL experiment (shown in Figure 1) which have been corrected for detection efficiency. Both the total data and data with a gate on break-ups not going via the ground state in  $^8\text{Be}$  are shown.



**Figure 4.** As Fig. 3, but data for the decay of  $^{12}\text{B}$ .

The absolute normalisation of the IGISOL data and KVI data are in good agreement in the region of overlap. The KVI data extend to lower energy and include the peak corresponding to the 7.654 MeV state. The peak below arises from energy deposition by  $\beta$ -particles from decays to bound states. The KVI spectra are shifted a small amount compared to the IGISOL data also due to the energy deposition by  $\beta$ -particles.

#### 4. Outlook and discussion

We are presently doing detailed fits to the two data sets using the R-matrix formalism. When only analysing decays via the ground state of  $^8\text{Be}$  (IGISOL data) our results are in agreement with the conclusions from our first round of experiments [18]. The inclusion of the other break-up channel in the R-matrix fits is non-trivial due to interference effects in both the  $^{12}\text{C}$  level and the break-up level and we have not yet reached final conclusions. At this stage it seems difficult to find a fit to the IGISOL data which predicts the measured branching ratio to the 7.654 MeV state in the two decays. The position of the  $2^+$  resonance at high energy was determined as 13.6 MeV in our first round of experiments [18], this value will increase with the new data due to this level having a very significant break-up channel to higher energies in  $^8\text{Be}$ . There still is no significant evidence for a  $2^+$  resonance in the 10-11 MeV region in  $^{12}\text{C}$  populated in these decays although this statement still needs to be accompanied by an upper limit on the branching ratio.

In order to make a proper comparison to the reaction results of Itoh *et al.* [12, 13] and Freer *et al.* [14] as well for the possible  $2^+$  resonance as for the dominating  $0^+$  resonance it would be desirable if the reaction data were properly analysed in the R-matrix approach since the assumption of Gaussian peaks for these broad resonances is ill justified. Note, that one

cannot apriori expect to find the same interference between  $^{12}\text{C}$  levels populated in reactions as extracted from  $\beta$ -decay data.

From a theoretical point of view it would be important to complement the prediction of a low lying  $2^+$  resonance with predictions of its breakup pattern and its population in  $\beta$ -decay and the reactions used by Itoh *et al.* [12, 13] and Freer *et al.*. Some of these predictions are already provided in recent publications [15], or discussed at this conference [26, 27], and it therefore seems possible that at the time of the next cluster conference in 2011 we will finally have a consistent theoretical and experimental understanding of the cluster structure of  $^{12}\text{C}$  including the position of the first  $2^+$  resonance above the 7.654 MeV state.

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